Draft version February 2, 2008
Preprint typeset using LaTeX style emulateapj v. 9/08/03

SUNYAEV-ZEL'DOVICH EFFECTS FROM QUASARS IN GALAXIES AND GROUPS

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Draft version February 2, 2008

ABSTRACT

The energy fed by active galactic nuclei to the surrounding diffuse baryons changes their amount, temperature, and distribution; so in groups and in member galaxies it affects the X-ray luminosity and also the Sunyaev-Zel'dovich effect. Here we compute how the latter is *enhanced* by the transient blastwave driven by an active quasar, and is *depressed* when the equilibrium is recovered with a depleted density. We constrain such depressions and enhancements with the masses of relic black holes in galaxies and the X-ray luminosities in groups. We discuss how all these linked observables can tell the quasar contribution to the thermal history of the baryons pervading galaxies and groups.

Subject headings: cosmic microwave background - galaxies: clusters: general - quasars: general

1. INTRODUCTION

The thermal energy content of the hot interstellar (ISM) or the intracluster medium (ICM) pervading galaxies or their groups and clusters can be probed with the Sunyaev-Zel'dovich (1980, SZ) effect. This arises when the hot electrons Compton upscatter some of the CMB photons crossing the structure; then the black body spectrum is tilted toward higher frequencies.

In the μwave band the tilt mimics a diminution $\Delta T_{\mu w} \approx -5.5\, y$ K of the CMB temperature, proportional to the Comptonization parameter $y \propto n\, T\, R$. This is evenly contributed by the electron density n and the temperature T; in fact, what matters is the electron pressure $p = n\, k\, T$ integrated along a line of sight (see Fig. 1):

$$y = 2\, \frac{\sigma_T}{m_e c^2} \int_0^R d\ell\, p(r)\ . \qquad (1)$$

To now, SZ signals have been measured in many rich clusters at levels $y \approx 10^{-4}$ or $\Delta T_{\mu w} \approx -0.5$ mK (see Rephaeli 1995; Birkinshaw 1999; Zhang & Wu 2000; Reese et al. 2002). These levels are consistent with ICM temperatures $kT \approx 5$ keV, sizes R of a few Mpcs, and central densities $n \approx 10^{-3}$ cm^{-3}. Similar values are indicated by the standard cluster view based on gravitational potential wells of virial depth $kT_v \propto G\, M/R$ dominated by the mass $M \sim 10^{15}\, M_\odot$ of the dark matter (DM). In such wells ICM masses $m \approx 0.2\, M$ are settled in hydrostatic equilibrium at specific energies $kT \approx kT_v$.

The above values also fit in with the X-ray luminosities $L_X \propto n^2 R^3 \sqrt{T} \approx 10^{44} - 10^{45}$ ergs s^{-1} emitted through thermal bremsstrahlung by the ICM. Groups, on the other hand, are underluminous relative to clusters; they emit far less than the baseline level $L_g \propto T_v^2$ scaled at constant $m \approx 0.2\, M$ after the DM rules. The observed $L_X - T_v$ correlation is clearly steeper, and goes from $L_X \propto T_v^3$ in clusters to $L_X \propto T_v^4$ or T_v^5 in poor groups, albeit with a wide variance (O'Sullivan, Ponman & Collins 2003). In other words, the ICM in groups appears to be underdense compared to clusters.

The origin of such lower densities is currently debated. One view centers on extensive radiative cooling (Bryan 2000) which would remove much low entropy gas. An alternative line of explanations (see Cavaliere, Lapi & Menci 2002, CLM02; and refs. therein) focuses on the energy injections affecting the ICM equilibrium while the DM is hierarchically accrued over dynamical timescales t_d. The inputs are provided when the baryons in galaxies condense to form stars possibly in starbursts, which then explode as SNe; alternatively or correlatedly (Menci et al. 2003, in prep.), the baryons accrete onto supermassive black holes (BHs) energizing active galactic nuclei (AGNs). Such feedback actions deplete the ICM density in the shallower potential wells by causing from inside thermal outflow and dynamical blowout; they also preheat the gas exterior to the newly forming structures, and so hinder its inflow.

In any case, for groups in *equilibrium* the values of y can be anticipated from the continuum L_X through the model-independent relation (Cavaliere & Menci 2001)

$$y/y_g = (L_X/L_g)^{1/2}\ (T/T_v)^{3/4}\ . \qquad (2)$$

Here $y_g \propto (1+z)^{3/2}\, T_v^{3/2}$ is the baseline value scaled to the formation redshift z (Cole & Kaiser 1988). So for groups where $L_X < L_g$ holds we expect *depressed* y.

Are *enhanced* SZ effects also possible, or even likely? What can these tell about the processes affecting n and T in groups and galaxies? Here we propose that a specific answer will come from SZ observations.

2. THE TRANSIENT REGIME

We start from recasting $y_g \propto E/R^2$ in terms of the gas thermal energy $E \propto p\, R^3$ at equilibrium. A small group or an early massive galaxy with their virial temperatures $kT_v \approx 1$ or 0.5 keV would produce SZ signals $\Delta T_{\mu w}/0.5\,\mathrm{mK} \approx -5$ or $-3 \times 10^{-2}\, (1+z)^{3/2}$. Larger energies $\Delta E \gtrsim E$ added to the ICM/ISM are expected to enhance the SZ signals yielding $y/y_g \approx \Delta E/E$.

Such may be the case with the AGNs (see Valageas & Silk 1999; Wu, Fabian & Nulsen 2000; Roychowdhury & Nath 2002) that produce large total outputs, typically around 5×10^{61} ergs over times around 10^8 yr comparable to t_d of their host structures. Such outputs can drive a blastwave sweeping out the gas mass and raising its

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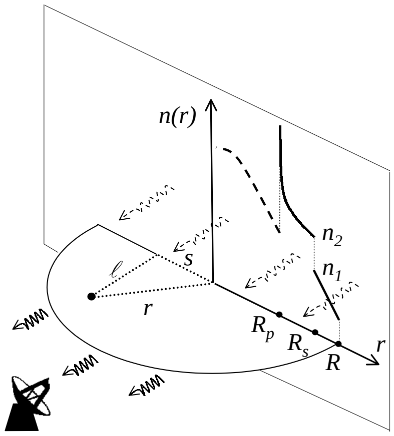

FIG. 1.— The geometry underlying Eq. (1). For a point in the structure r is the radial coordinate, s is its projection on the plane of the sky, and ℓ is the coordinate along the line of sight. On the vertical axis we outline the initial density run, and the flow perturbed by the AGN-driven blastwave.

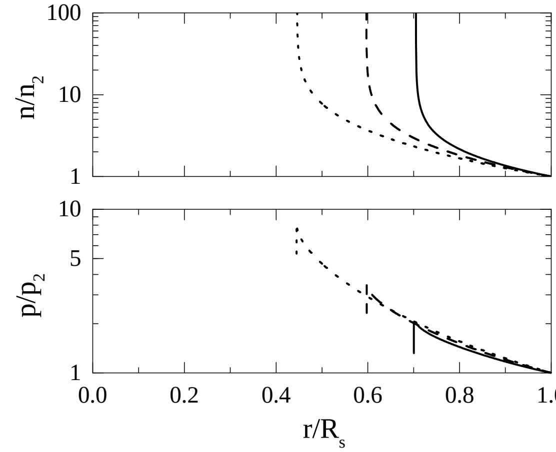

FIG. 2.— Radial distribution of density and pressure in the blastwave, relative to the post-shock values n_2 and p_2. *Solid lines* refer to a strong shock with $\Delta E/E = 3$, *dashed lines* to an intermediate shock with $\Delta E/E = 1$, and *dotted lines* to a weak shock with $\Delta E/E = 0.3$; the corresponding piston positions are given by $\lambda \approx 0.7$, 0.6, 0.45.

pressure (see Platania et al. 2002; also Yamada & Fujita 2001).

We will see that the blast is *constrained* by the coupling of the AGN outputs to the surrounding gas, and *restrained* by the initial pressure and the DM gravity. We describe the blast flow on using the self-similar hydrodynamical solutions presented by CLM02. The simplest one obtains when the energy $\Delta E(t) \propto t$ is delivered over times of order t_d at the center of an isothermal configuration for the DM and for the gas with $n(r) \propto p(r) \propto r^{-2}$. Then the leading shock moves out with uniform Mach number $\mathcal{M}$, i.e., with radius $R_s = \dot{R}_s\, t$; the kinetic, the thermal and the gravitational energies of the perturbed gas all scale like R_s. So we can consistently define inside R_s the total initial energy E (modulus); most important, our solutions provide realistic predictions not only for *strong* blasts but also for the *weak* ones driven by constrained values of $\Delta E/E$.

Detailed profiles are presented in Fig. 2. Note that the perturbed flow is confined to a shell; this is bounded by the leading shock at R_s, and by a trailing contact surface ("piston") located at $\lambda\, R_s < R_s$ where the density diverges weakly while the pressure is finite. So the relevant quantities may be also obtained from the simple and precise "shell approximation" (see Ostriker & McKee 1988), which provides the energy balance in the form

$$\Delta E - E = \frac{1}{2}\, m\, v_2^2 + \frac{3}{2}\, \langle p \rangle\, V - \frac{G\, M\, m}{R_s}\ . \qquad (3)$$

Here $\langle p \rangle = p_2\, (5\, \mathcal{M}^2 + 7)/(5\mathcal{M}^2 - 1)$ is the mean pressure within the shell volume $V = 4\pi\, R_s^3\, (1-\lambda^3)/3$, important for the SZ signals; M and m are the DM and the gas masses within R_s. The Rankine-Hugoniot jump conditions yield the postshock quantities: the velocity $v_2 = 3\, \dot{R}_s\, (\mathcal{M}^2 - 1)/4\, \mathcal{M}^2$, the pressure $p_2 = p_1\, (5\mathcal{M}^2 - 1)/4$ and the density $n_2 = 4\, n_1\, \mathcal{M}^2/(\mathcal{M}^2 + 3)$, given the preshock values p_1, n_1.

As to the energy ΔE actually injected over t_d, the paradigm of supermassive BHs for the AGNs implies $\Delta E \approx 2 \times 10^{62}\, f\, (M_{BH}/10^9\, M_\odot)\, (1+z)^{-3/2}$ ergs when the mass M_{BH} is accreted with conversion efficiency of order 10^{-1}. The fractional energy f coupled to the surrounding gas is poorly known. Including inefficiencies due to low momentum transfer, non-spherical geometries and covering factors it may range from $f \approx 10^{-2}$ for radio-quiet, to some 10^{-1} for strongly absorbed (BAL) or radio-loud quasars, a small minority. Average values $f \approx 5 \times 10^{-2}$ are shown below to be consistent with the observations both of the relic BHs in galaxies and of L_X in groups.

The ratio $\Delta E/E$ is seen from Eq. (3) to be uniform, and to constitute a key parameter for the shock strength. Table 1 presents quantities relevant to our computations of SZ signals.

We have extended our basic solution to initial density runs $n \propto r^{-\omega}$, with $2 \leq \omega < 2.5$. Then the initial temperature declines as $T(r) \propto r^{2-\omega}$, and the shock decelerates as $R_s \propto t^{2/\omega}$, again under self-similarity; this also implies declining source luminosities with $\Delta E(t) \propto t^{2\,(5-2\,\omega)/\omega}$. Table 1 shows that larger ω yields somewhat higher $\mathcal{M}$ and $\langle p \rangle$ at given $\Delta E/E$.

3. TRANSIENT AND EQUILIBRIUM SZ EFFECTS

In computing how y is *enhanced* during the blast transit, we focus on $\bar{y} \propto R^{-2} \int ds\, s\, y(s)$ averaged over the structure area, which will subtend small angles $R/D_A \lesssim 1'$ for an early group or galaxy. Normalizing the shock position as $x \equiv R_s(t)/R$, we find the full signal

$$\frac{\bar{y}}{\bar{y}_g} = \frac{\langle p \rangle}{3\, p_1}\, (1-\lambda^3)\, x + \sqrt{1-x^2} \simeq \frac{\langle p \rangle}{3\, p_1}\, (1-\lambda^3)\ , \qquad (4)$$

in terms of $\bar{y}_g = (4\, \sigma_T/m_e c^2)\, p(R)\, R$. The last approximation applies for $x \approx 1$, which maximizes the transit time in the structure and optimizes the observability.

Strong SZ signals are seen from Eq. (4) and Table 1 to require substantial blasts driven through the ISM or the ICM, i.e., input ΔE competing with the equilibrium value E. For $\omega = 2$ the latter writes $E \approx 2 \times 10^{61}\, (kT/\mathrm{keV})^{5/2}\, (1+z)^{-3/2}$ ergs; so the ratio reads

$$\frac{\Delta E}{E} = 0.1\, \frac{f}{10^{-2}}\, \frac{M_{BH}}{10^9\, M_\odot}\, \left(\frac{kT_v}{\mathrm{keV}}\right)^{-5/2}\ . \qquad (5)$$

Table 1. Relevant Blastwave Quantities

	$\omega = 2$		$\omega = 2.4$	
$\Delta E/E$	$\mathcal{M}$	$\langle p \rangle/p_1$	$\mathcal{M}$	$\langle p \rangle/p_1$
0.3	1.2	3.6	2.1	17.8
1	1.5	4.6	3.0	21.7
3	1.9	6.3	4.7	32.6

Here M_{BH} is the mass accreted within $t_d \propto (1+z)^{-3/2}$ by the central BH in a massive galaxy, or by the sum of BHs shining within a group. Eq. (5) yields ΔE close to E for a poor group with $kT_v \approx 1$ keV and $M_{BH} \approx 10^9\, M_\odot$. In going toward local, rich clusters M_{BH} clearly lags behind M, so $\Delta E/E$ will decrease strongly, see CLM02 for details.

At the other end, toward galaxies $\Delta E/E$ is constrained not to exceed a few, lest the gas contained within kpcs and the accretion it feeds are cut down (see Silk & Rees 1998). The pivotal value $\Delta E/E \approx 1$ recast in terms of the DM velocity dispersion $\sigma = (kT_v/0.6\, m_p)^{1/2}$ reads

$$M_{BH} \approx 2 \times 10^9 M_\odot \left(\frac{f}{10^{-2}}\right)^{-1} \left(\frac{\sigma}{300\,\mathrm{km\,s^{-1}}}\right)^5 . \quad (6)$$

Converting to the bulge dispersion $\sigma_\star \propto \sigma^{1.2}$ (see Ferrarese 2002) yields $M_{BH} \propto \sigma_\star^4$. For values $f \approx 5 \times 10^{-2}$ the relation accords with the observations in Tremaine et al. (2002).

Our results are represented in Fig. 3 vs. the depth kT_v of the host potential well. The square illustrates the *minimal* enhancement we expect from an early group at $z = 1.5$ with $kT_v = 1$ keV, $f = 5 \times 10^{-2}$ and $M_{BH} = 10^9\, M_\odot$, so with $\Delta E = 0.5\, E$. The bar gives a realistic upper *bound* for structures with steeper $n(r)$, namely, with $\omega = 2.4$; here E is larger but the energy release is more impulsive, resulting (see Table 1) in stronger signals. With radii $R \approx 250$ kpc, the angular sizes $2\, R/D_A \approx 1'$ are close to their minimum in the concordance cosmology (cf. Bennett et al. 2003). Comparable resolutions will soon be achieved, see § 4.

The circles in Fig. 3 represent our results for a massive ($\sigma = 300$ km s^{-1}, $R \approx 100$ kpc) and still gas-rich ($m = 0.15\, M$) protogalaxy at $z = 2.5$. The open circle refers to $\Delta E = E$ or $M_{BH} = 6 \times 10^8\, M_\odot$; the filled one to $\Delta E = 3\, E$ or $M_{BH} = 2 \times 10^9\, M_\odot$, just compatible with the scatter in the $M_{BH} - \sigma$ correlation. The related angular sizes are around $0.5'$; with resolution fixed at $2\,\theta_b \approx 1'$, the signals will be diluted after $(R/D_A\, \theta_b)^2 \approx 1/4$ and scaled down to $\Delta T_{\mu w} \approx -20\,\mu$K.

The inset represents the corresponding statistics. This is evaluated on inserting the related blue luminosities $L = \Delta E/10\, f\, t_d \approx 5 \times 10^{45}$ and 1.5×10^{46} ergs s^{-1} (with a bolometric correction 10) in the quasar luminosity function observed for $z \lesssim 2.5$ by Boyle et al. (2000), and discussed by Cavaliere & Vittorini (2000, CV00). In terms of the cumulative fraction of bright galaxies hosting a type 1 quasar brighter than L, this reads

$$N(L)\, L \approx 2\, 10^{-2}\, (1+z)^{3/2}\, (L_b/L)^{2.2} , \quad (7)$$

beyond the break at $L_b = 5 \times 10^{45}\, [(1+z)/3.5]^3$ ergs s^{-1}. The same luminosity function interpreted in terms of interactions of the host galaxy with its group companions (CV00) yields a few signals per 10 poor groups, with the strength represented by the square in Fig. 3.

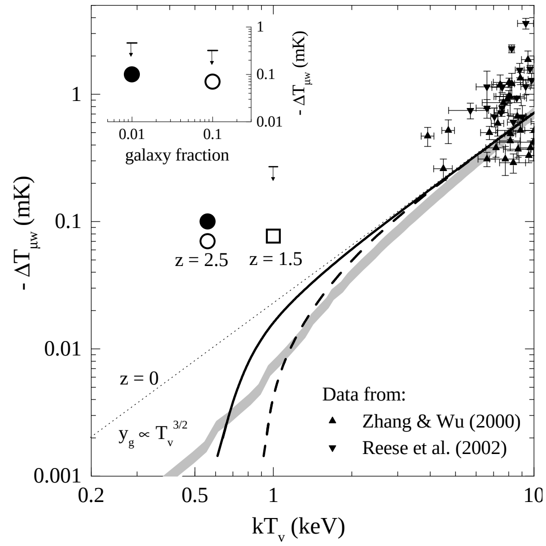

Fig. 3.— Predicted SZ signals as a function of the virial temperatures of galaxies, groups and clusters. *Dotted line*: the baseline y_g at $z = 0$. *Shaded strip*: central signals from gas in the equilibrium set by SN preheating (Cavaliere & Menci 2001). *Thick lines*: same for feedback from AGNs with $M_{BH} = 10^9\, M_\odot$ and coupling $f = 3 \times 10^{-2}$ (*solid*) or $f = 10^{-1}$ (*dashed*). *Square*: area-averaged, undiluted signal from a group at $z = 1.5$, driven by AGN activity with $M_{BH} = 10^9\, M_\odot$ and $f = 5 \times 10^{-2}$; the bar represents the bound for $\omega = 2.4$. *Circles*: same from a massive galaxy at $z = 2.5$, for $\Delta E = E$ (*open*) or $3\, E$ (*filled*); the inset specifies the statistics.

After the passage of the blast, the gas recovers hydrostatic equilibrium. This may be described by $n(r) = n(R)\, \exp(\beta\, \Delta\phi)$ for a nearly isothermal ICM in the (normalized) DM potential well $\Delta\phi(r)$, see Cavaliere & Fusco-Femiano (1976). The blast heats up the gas so decreasing the value of the parameter $\beta = T_v/T$, that we reset on using T averaged over the mass in the shell. The blast also ejects gas and depletes all densities; we reset $n(R)$ by requiring the volume integral of $n(r)$ to equal the gas mass left by the blast inside R at $t = t_d$.

The equilibrium SZ effect is then computed after Eq. (1), and the resulting signals are also plotted in Fig. 3. We recall from CLM02 that the equilibrium also provides good fits to the observed L_X in groups for the *same* coupling $f \approx 5 \times 10^{-2}$, consistent with Eq. (6).

4. DISCUSSION AND CONCLUSIONS

This Letter centers on how the SZ effect is affected by the energy fed back by AGNs into the surrounding gas. We predict both transient, *enhanced* and long-term, *depressed* SZ signals to be produced by an energy addition ΔE to the equilibrium value E.

In 1 keV groups the condition $\Delta E \lesssim E$ holds, and the AGN feedback has a considerable impact. A blast is driven through the gas; during its transit the area-averaged SZ signal is enhanced as the gas is just redistributed while its pressure is *raised*. But eventually a considerable gas fraction is *ejected*; so n is depleted and $y \propto n\,T$ is decreased at equilibrium. We have computed these effects under the *restraints* set to (weak) blast propagation by initial pressure and DM gravity.

The result on the SZ effect is twofold: on scales $1'$ we

predict *transient* enhancements up to $\Delta T_{\mu w} \approx -80\,\mu$K (a representative example at $z \approx 1.5$ is given in Fig. 3), followed by *long-term* depressions. The latter correlate after Eq. (2) with the equilibrium X-ray luminosities $L_X \propto n^2\sqrt{T}$ which are very depressed.

Larger $\Delta E/E$, yet *constrained* by Eq. (6), yield stronger SZ enhancements in gas-rich massive protogalaxies with halo radii $R \sim 100$ kpc; representative examples are shown by the circles in Fig. 3. With angular sizes $0.5'$, these may be diluted down to $\Delta T_{\mu w} \approx -20\,\mu$K when observed at a resolution around $1'$.

Such resolutions will be achieved by several instruments now being built or designed, enabling "blind" sky surveys for SZ signals to μK sensitivities over tens of square degrees (see Carlstrom, Holder & Reese 2002). In particular, promising perspectives are offered by multibeam, high frequency radio receivers like OCRA (Browne et al. 2000), and also by interferometers equipped with wide-band correlators like ATCA, SZA (Holder et al. 2000), AMI (Jones 2002), and AMiBA (Lo 2002). The SZ signals we consider may contribute equally or more than clusters to the excess power already detected at high multipoles with BIMA (Dawson et al. 2002). In the (sub)millimetric band the SZ signal is positive, and will be accessible to large bolometer arrays like BOLOCAM, whose developments will enable deep, wide surveys (Mauskopf et al. 2002). Eventually, ALMA (`http://www.alma.nrao.edu/`) will provide in selected areas higher resolution for both sides of the SZ effect.

Enhanced signals as discussed here would constitute *signatures* of strong feedback caught in the act. This is specific of AGNs, since SNe feed back at most 0.3 keV/particle (see CLM02); on the other hand, extended cooling which depletes n without increasing T hardly could enhance $y \propto n\,T$. Interlopers might be introduced by merging events; however, these primarily govern the growth of the DM halos and set the virial $T_v \propto M^{2/3}$ included in our baseline $y_g \propto T_v^{3/2}$. Only an exceptional major merging may contribute an energy step sizeable but still bound by $\Delta E < E$. Even this produces transonic inflows in the high-T_v partner gas, originating limited warmer features as picked up by highly resolved X-ray studies of clusters. Still smoother inflows are produced by SN preheating (see Voit et al. 2003), while stronger blasts are driven by AGNs, in the galaxies and groups that we propose here as primarily SZ objects.

Detecting 10 such signals will require surveys over 500 arcmin^2 at $1'$ resolution, based on the conservative surface density of 10^2 powerful quasars/deg^2 consistent with Eq. (7). For groups our evaluations (Fig. 3) lead to SZ enhancements in the range $\bar{y}/\bar{y}_g \approx 1.2 - 4$ over a depressed if wrinkled landscape. In fact, for $kT_v \approx 1$ keV the baseline y_g is affected mainly by SNe (see Fig. 3); these depress the average levels somewhat, and cause at $z \approx 1.5$ a 10% relative scatter (at 96% confidence). This landscape may be sampled or bounded from independent groups catalogued at comparable z. For massive protogalaxies intrinsically stronger enhancements, less depression and narrower scatter obtain. The candidate peaks are to be followed up with ALMA for higher resolutions; in addition, optical z, and optical σ or X-ray T will require current or moderately extrapolated techniques (cf. Rosati, Borgani & Norman 2002; Shields et al. 2003).

In conclusion, we expect that AGN energy outputs around 10^{62} ergs with coupling $f \sim 5 \times 10^{-2}$ leave two consistent *relics*: the depressed X-ray luminosities L_X in local galaxies and groups (see CLM02); the $M_{BH} - \sigma$ relation on subgalactic scales (Eq. 6). Relatedly, on intermediate scales we evaluate here (Fig. 3) *transient* SZ signals standing out of a generally depressed landscape. Such signals can provide real time *evidence* of AGN feedback acting on the diffuse baryons in galaxies and groups. The evidence should be looked for primarily in the SZ surveys that will be soon available.

We thank N. Menci and our referee for helpful comments.

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